Controlling Wind Turbines for Ancillary Services: An Analysis of Capabilities and Trade-offs

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NAWEA 2013 Symposium
Wed, Aug 7, 2013
Boulder, CO

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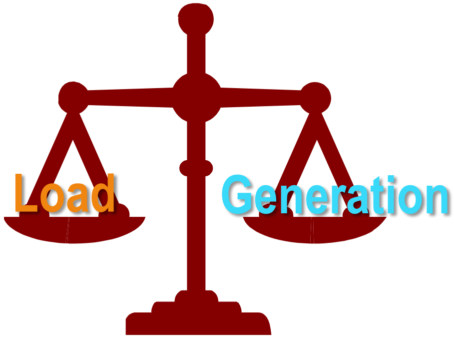
Presentation Outline

- Active Power Control (APC) Overview
  - Frequency control basics
  - Motivation for APC in wind energy
- Wind Turbine APC Control System
- Wind turbine participation in regulation
  - Damage Equivalent Loads
  - Regulation performance
- Conclusions
- Future research

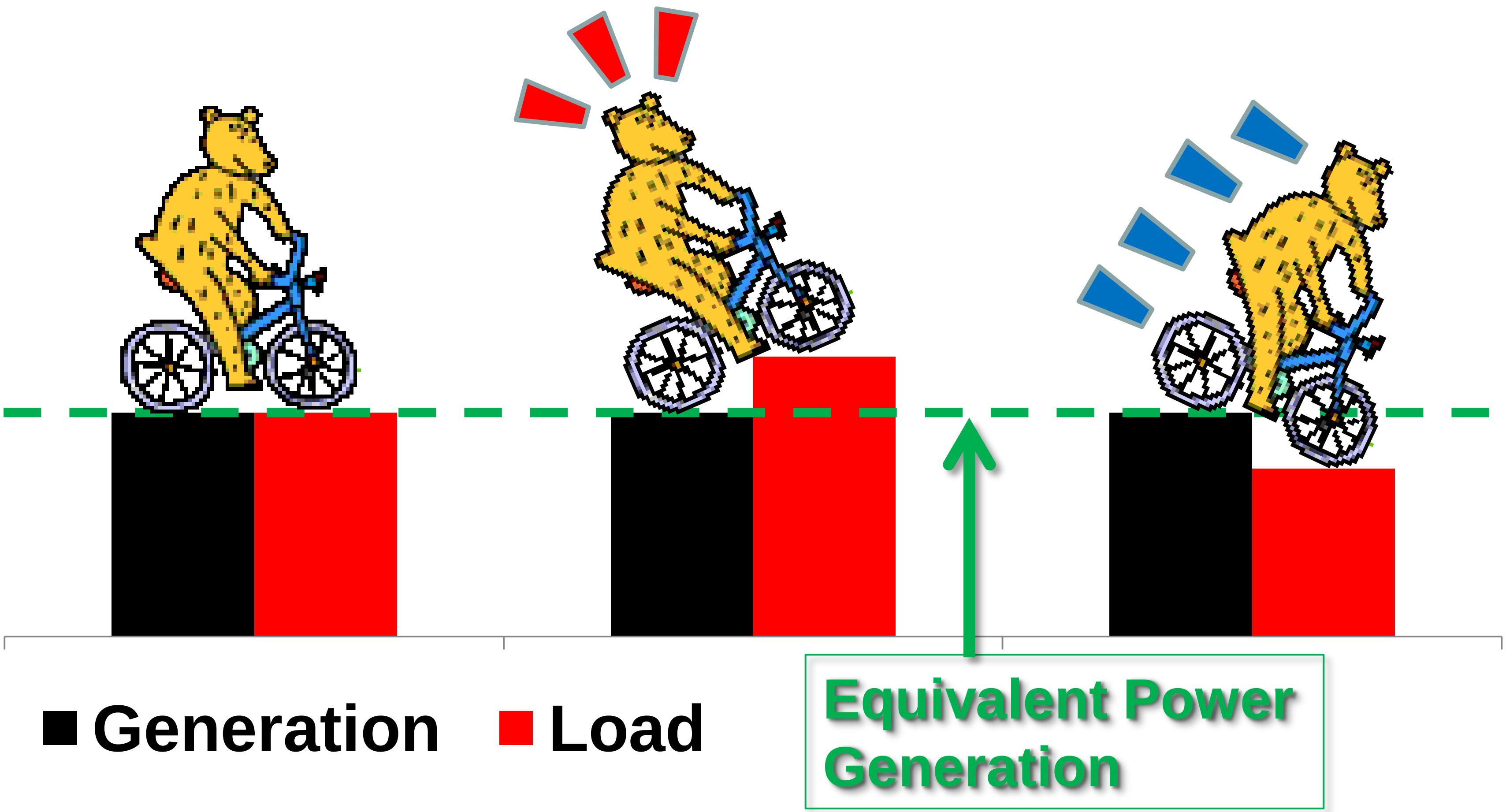
Importance of Frequency Control

- **For reliability:** The active power generation and load must remain balanced on the electrical grid
  - Imbalances cause frequency variations, when large enough can induce load shedding or even blackouts
- Most load cannot be controlled, so frequency control is primarily performed by the generation (through APC)
- Variability of wind has increased the ‘integration cost’
  - Cost to procure regulation reserves to handle variations
  - Improved forecasting and 5 min. markets have reduced this cost



Frequency Fluctuations

f_{grid}=60 Hz f_{grid}<60 Hz f_{grid}>60 Hz



Operating Reserves

Operating Reserves

Following Reserves - or - Tertiary (Manual)

Regulating Reserves - or - Secondary (Automatic)

Primary Frequency Response (PFR) (Automatic)

Power commands
- set-point
- de-rating
- curtailment

Automatic Generation Control (AGC)

A. Buckspan
(Graduate Student Session)

FERC Order 755

Performance based compensation

Capacity, Accuracy, Speed

For more detailed information, see: **Operating Reserves and Variable Generation**
E. Ela, M. Milligan, and B. Kirby NREL/TP-5500-51978, August 2011

Balancing Requirements- BAs

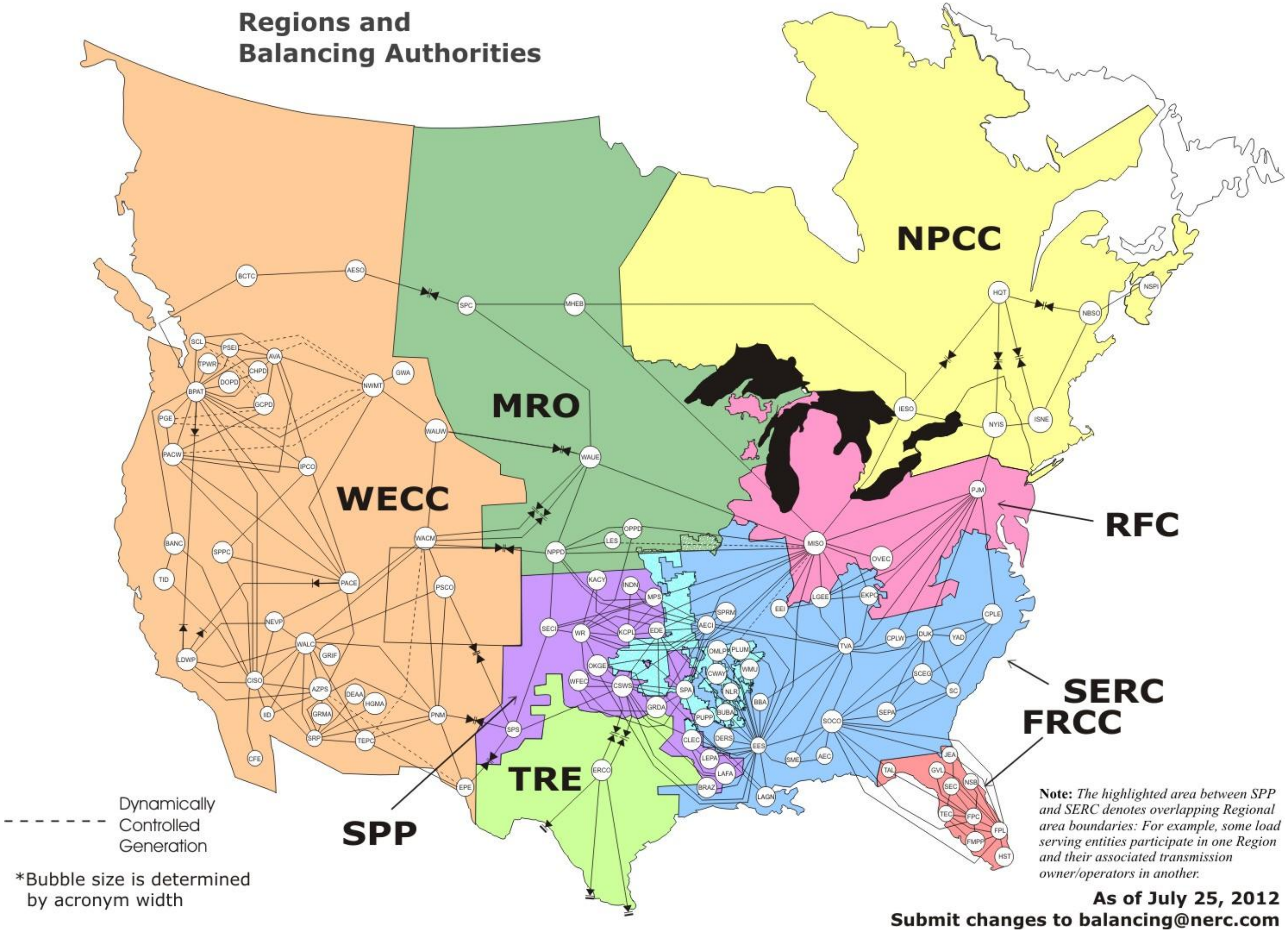
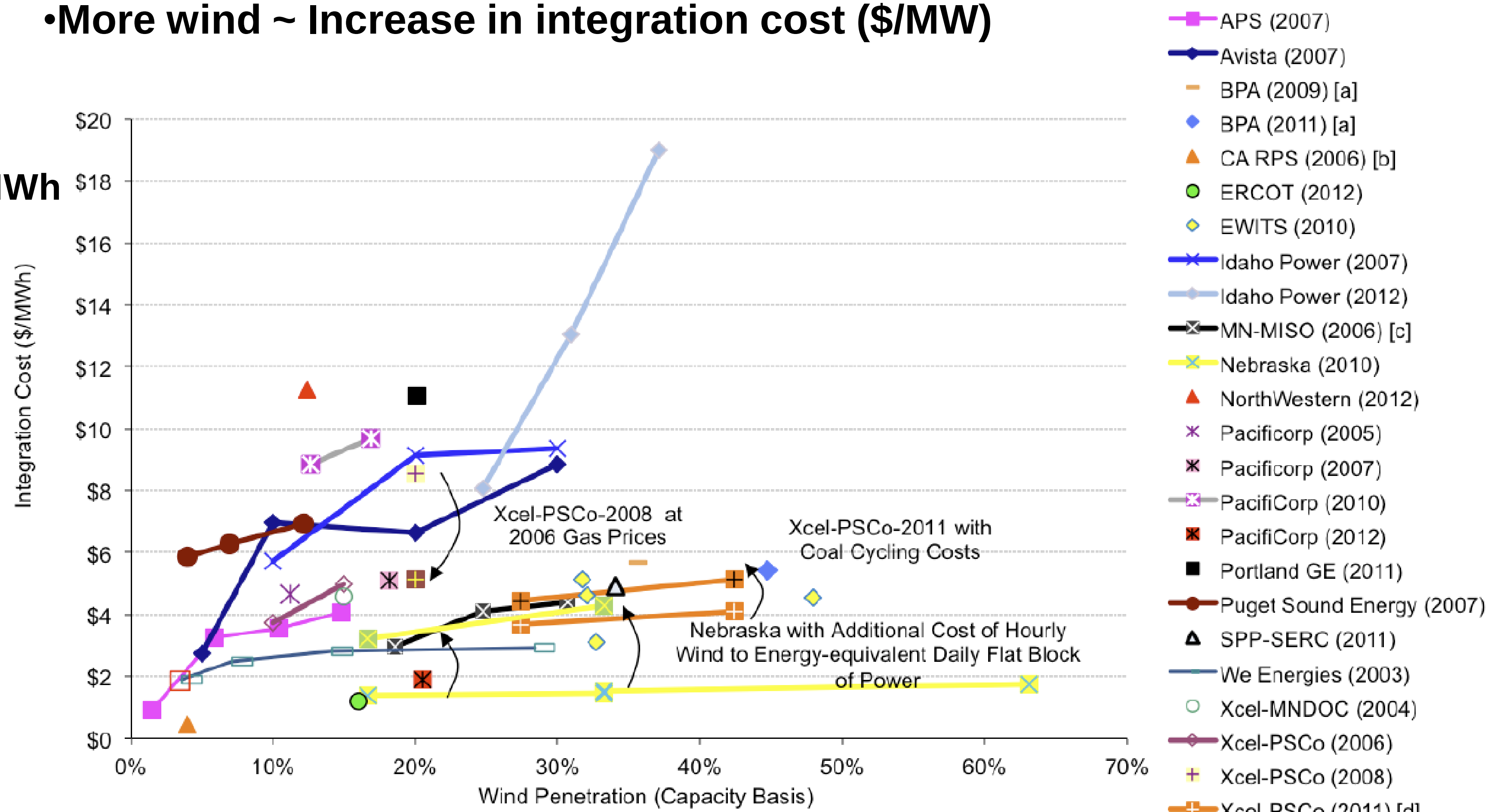


Image Source: NERC

"Integration Cost" of Wind

•More wind ~ Increase in integration cost ($/MW)

$/MWh



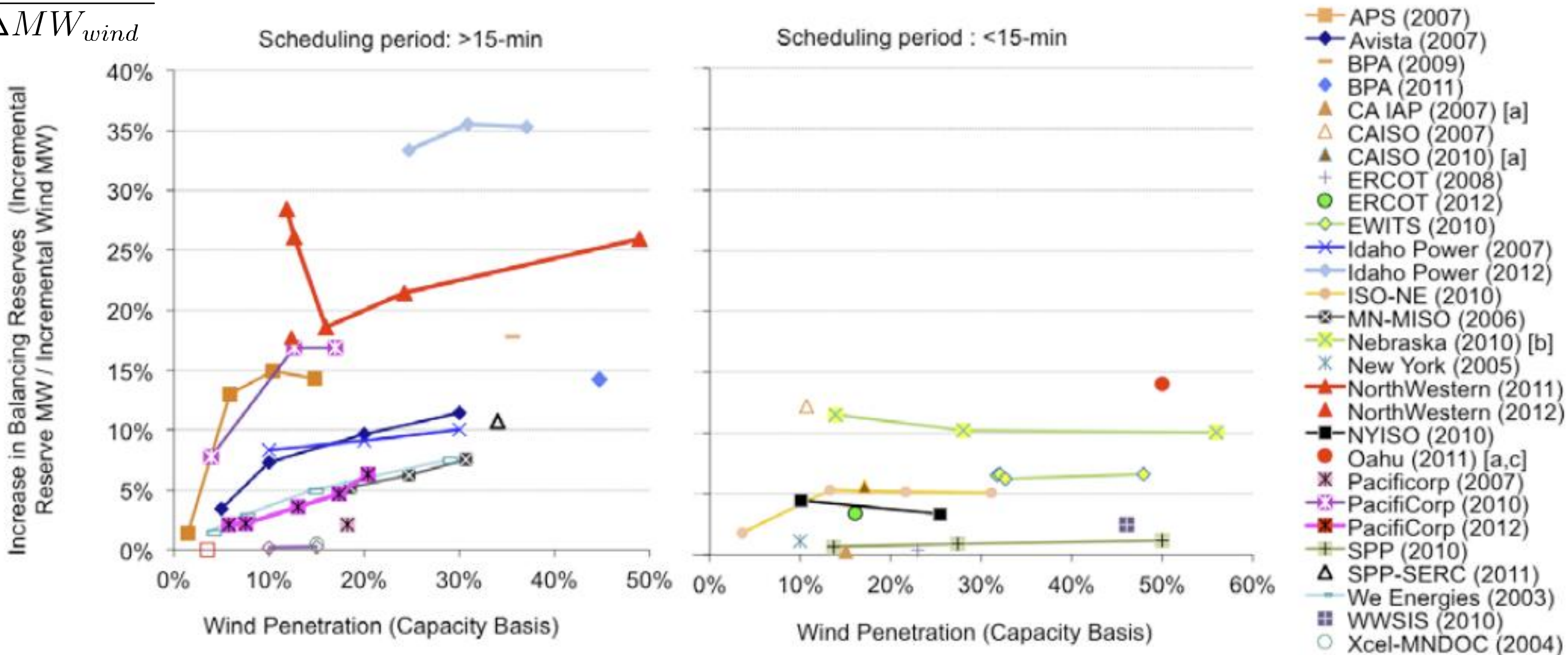
"Wind Penetration" = % of power generated by wind

Source: *2012 Wind Technologies Market Report*, U.S. Department of Energy, August 2013

"Integration Cost" of Wind

- More wind ~ Increase in operating reserves per MW of wind
- Reducing scheduling period to 5 minutes reduces this burden

$$\frac{\Delta MW_{reserve}}{\Delta MW_{wind}}$$



"Wind Penetration" = % of power generated by wind

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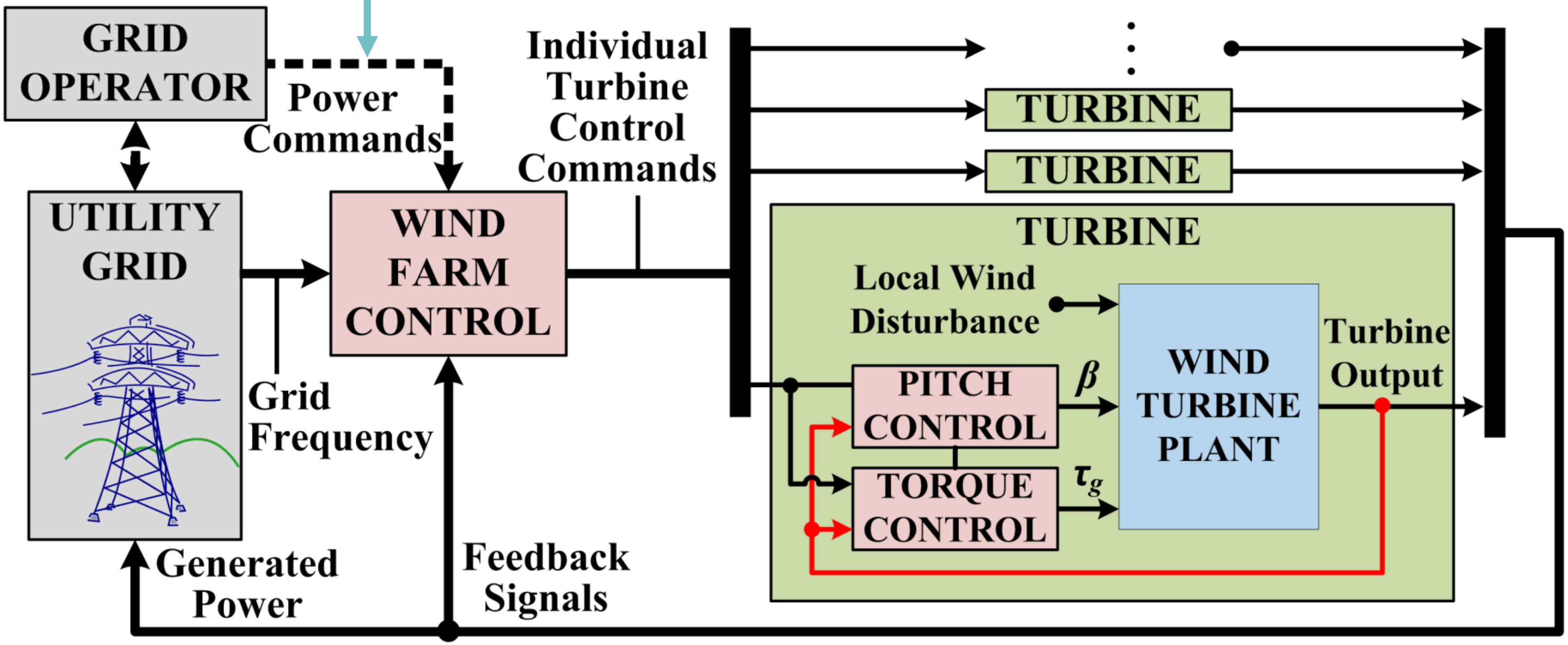
APC with Wind Turbines

- De-rating commands (set-points or curtailment)
- AGC power command (regulation/balancing)



Wind Turbine APC Controller

Goal: Design a simple, practical, and implementable wind APC control system capable of:

3 de-rating modes:

- Power set-point
- Maintain specified power reserve
- Capture specified percentage of available power

Providing Primary Frequency Response (PFR)

Participate in regulation/AGC (power tracking)

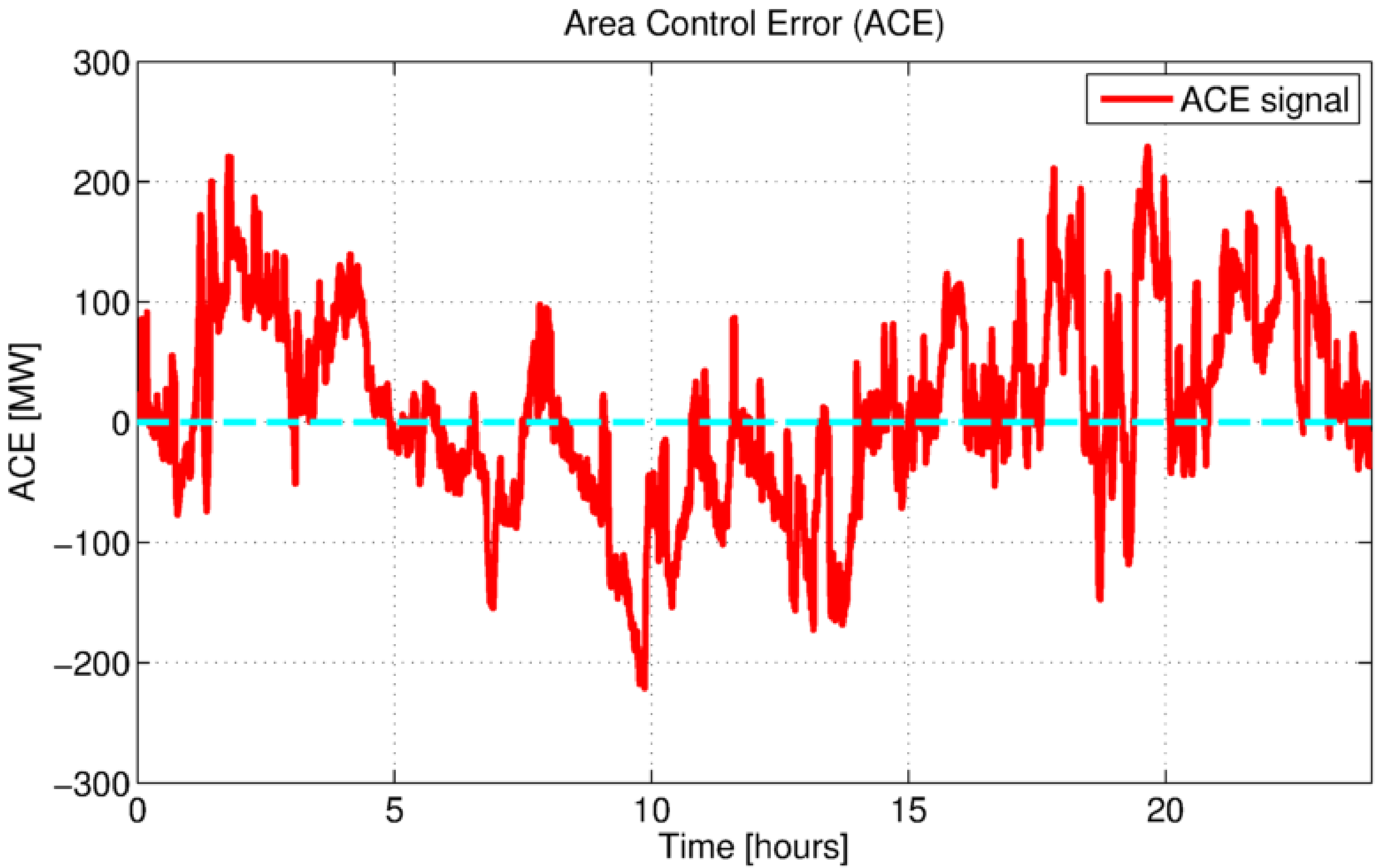
Field tested on NREL's 550kW 3-bladed Controls Advanced Research Turbine (CART3)

Tested PFR, all de-rating modes, and AGC

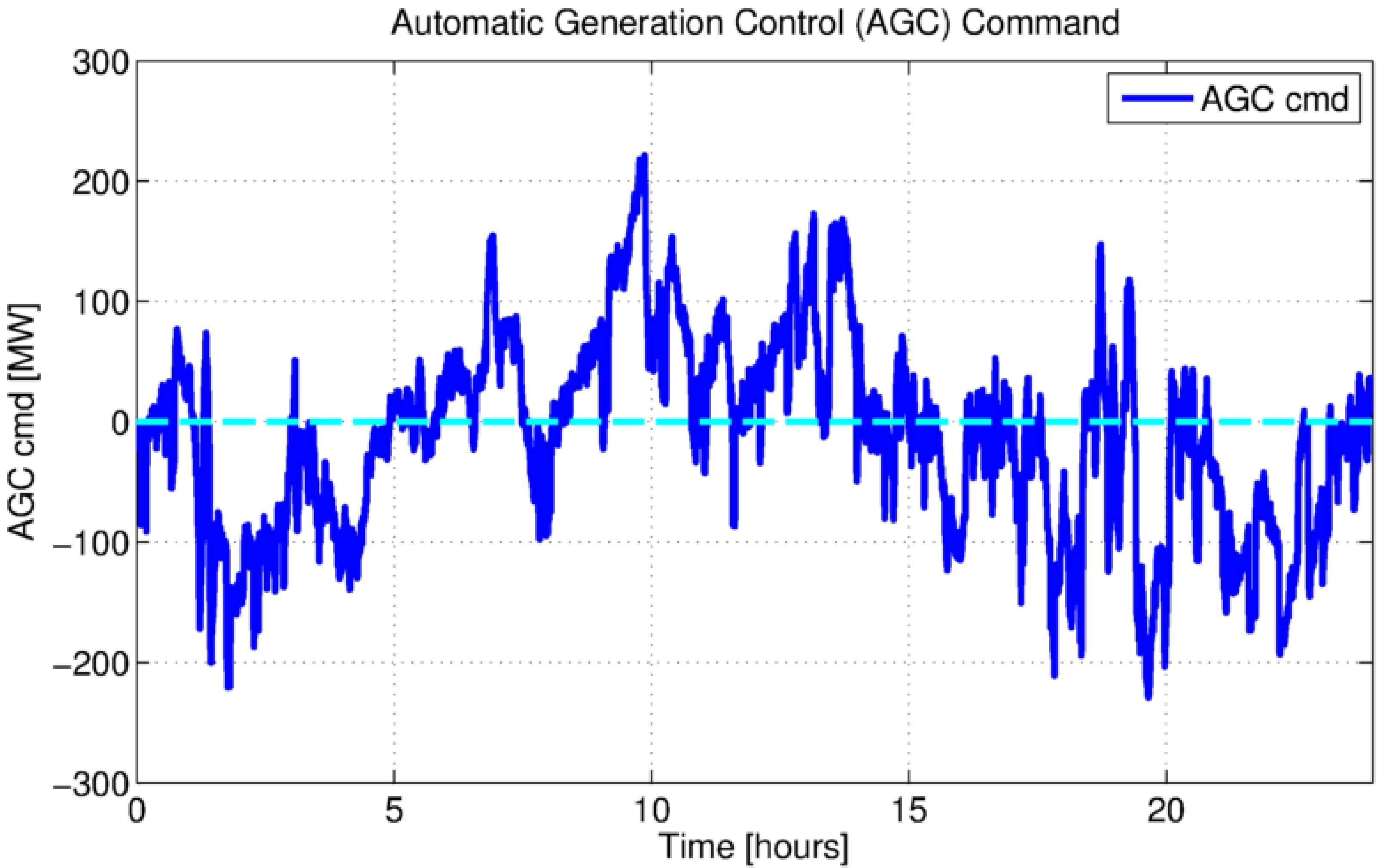
Leading manufacturers have similar capabilities, our goal was to publish in public domain and evaluate capabilities/limitations

For further details of wind turbine control system see: J. Aho, A. Buckspan, L. Pao and P. Fleming, "An Active Power Control System for Wind Turbines Capable of Primary and Secondary Frequency Control for Supporting Grid Reliability," in *Proc. of the 51st AIAA Aerospace Sciences Meeting*, Grapevine, 2013.

AGC Power Command

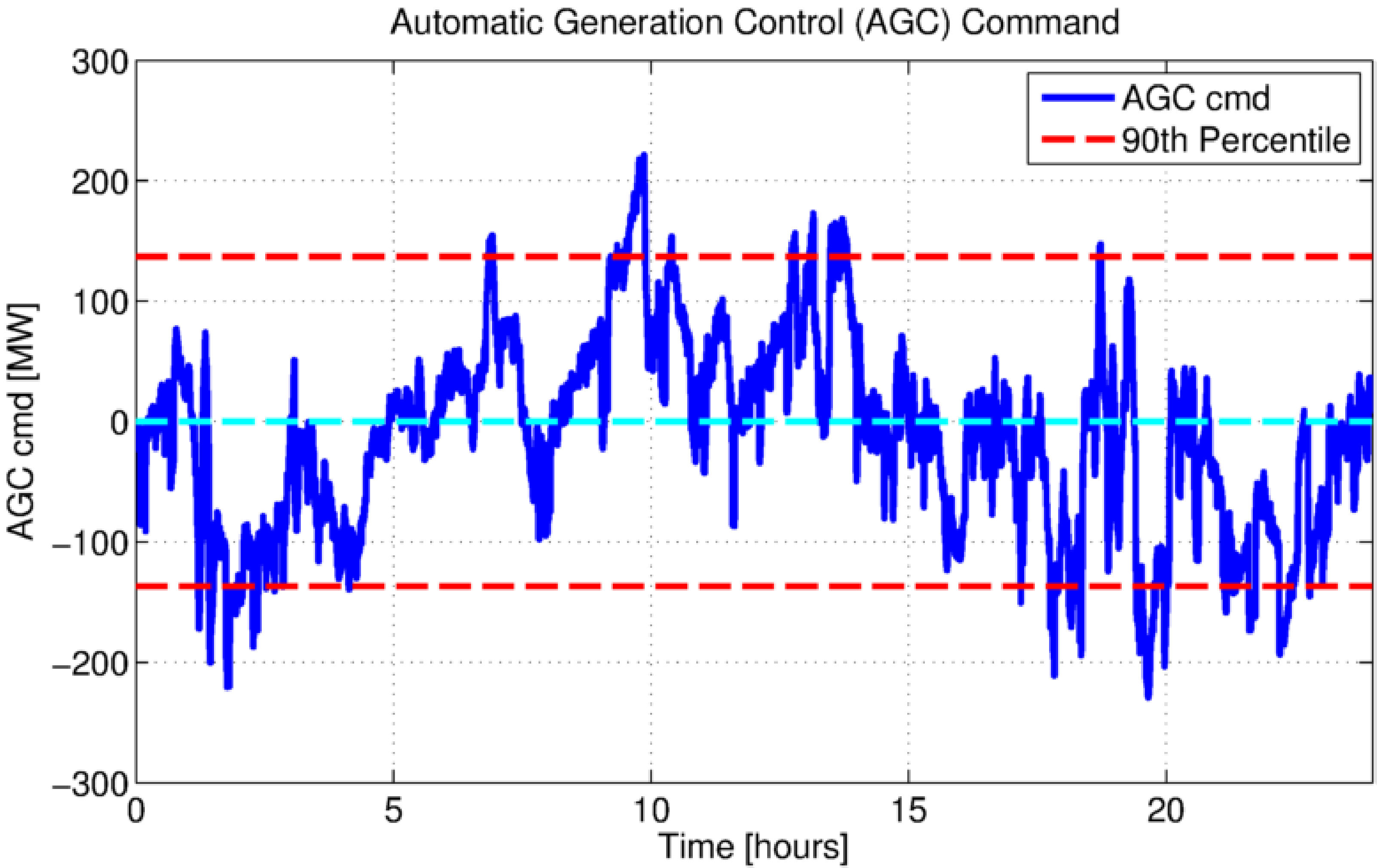


AGC Power Command



AGC commands sent out every 4 seconds

AGC Power Command



AGC commands sent out every 4 seconds

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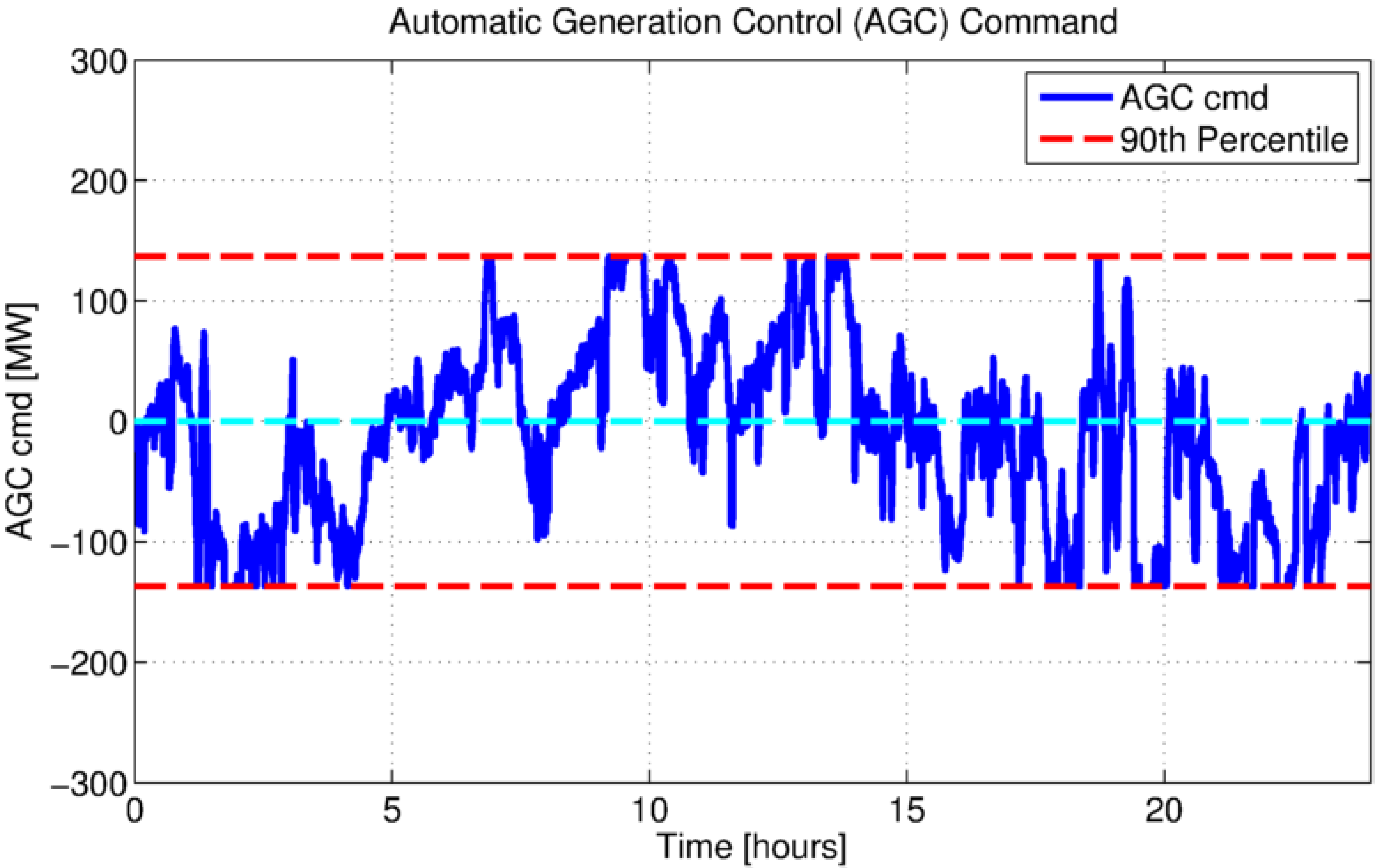

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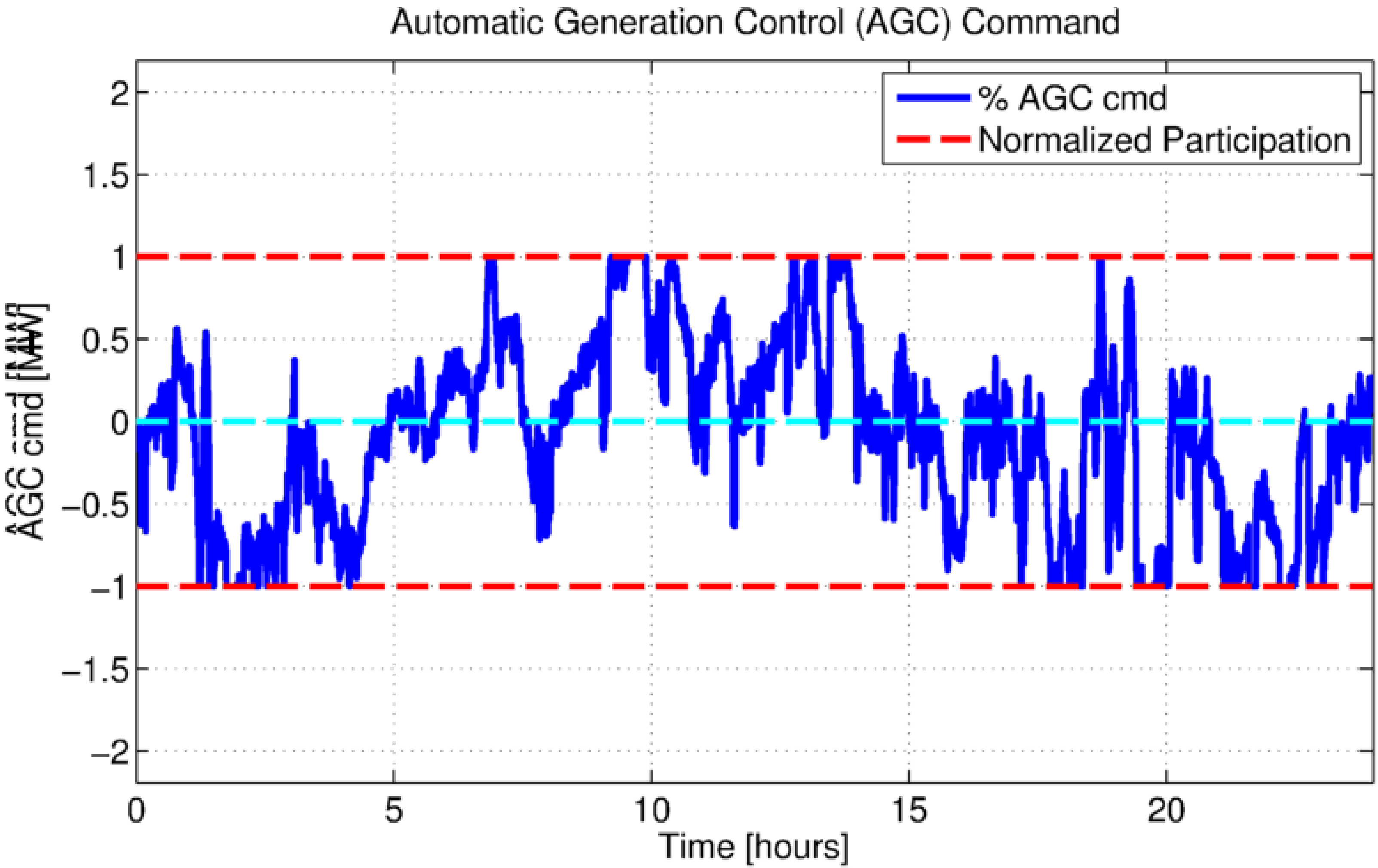
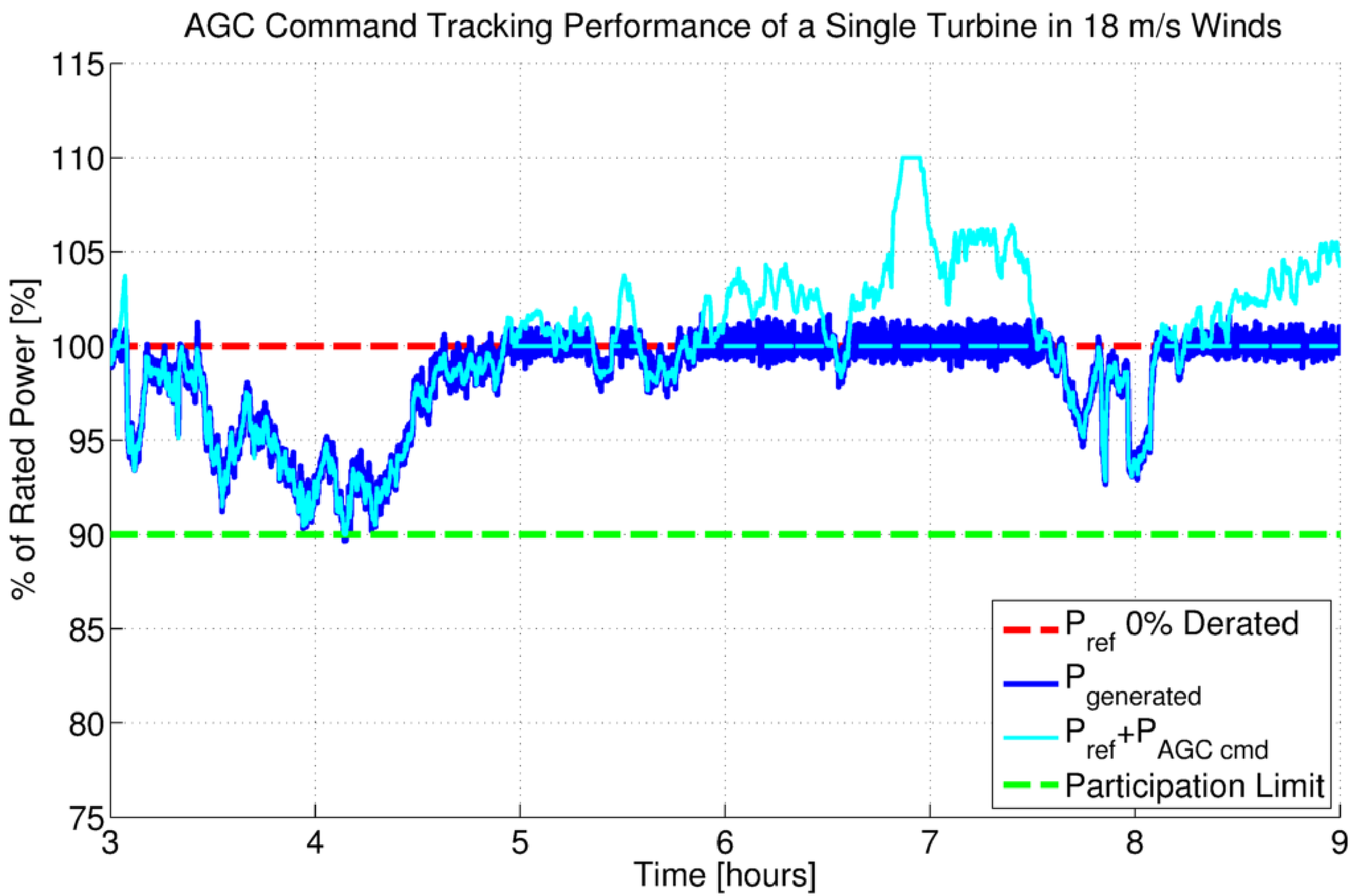
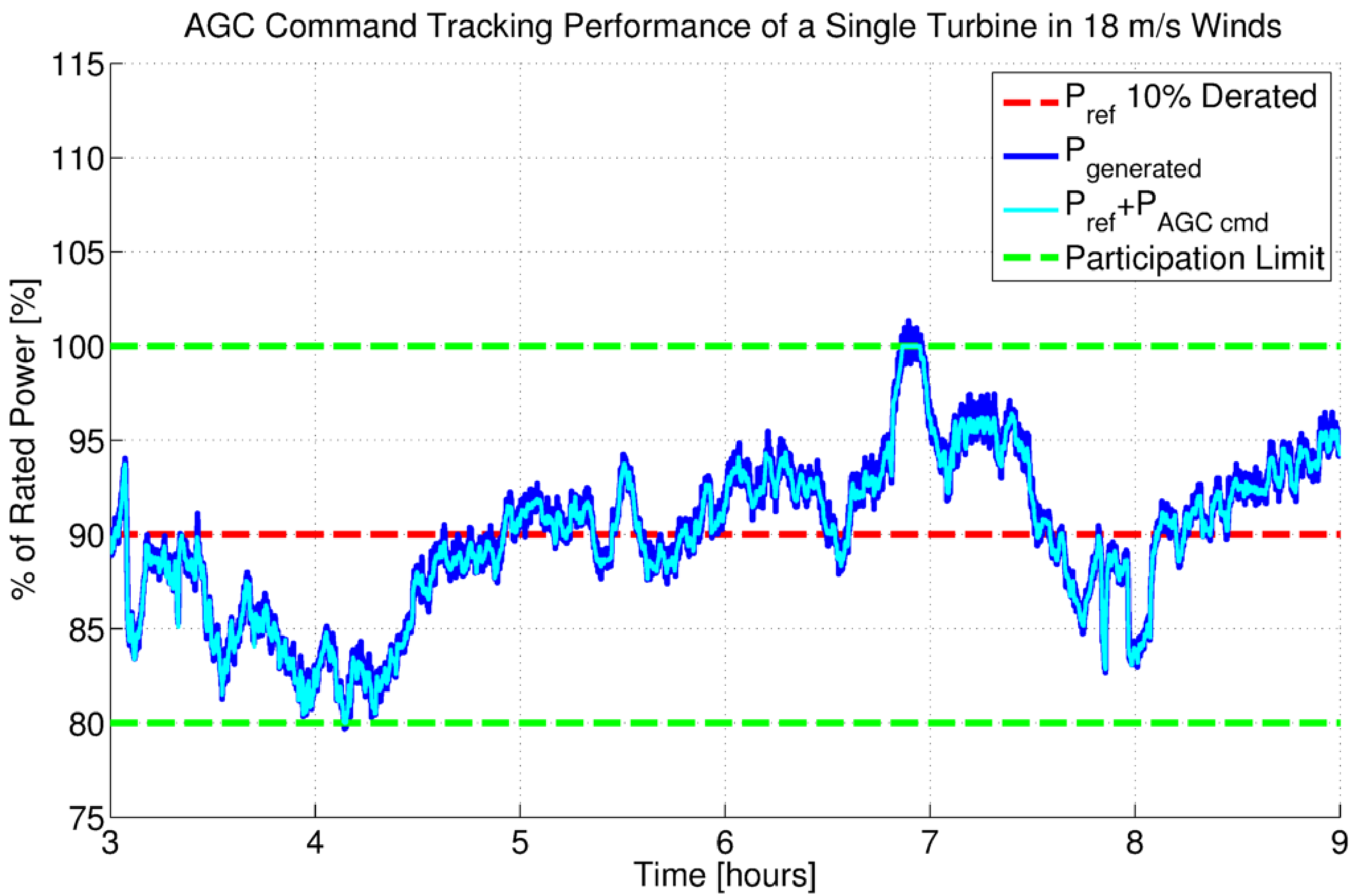


AGC commands sent out every 4 seconds

Regulation Down- 10% Participation

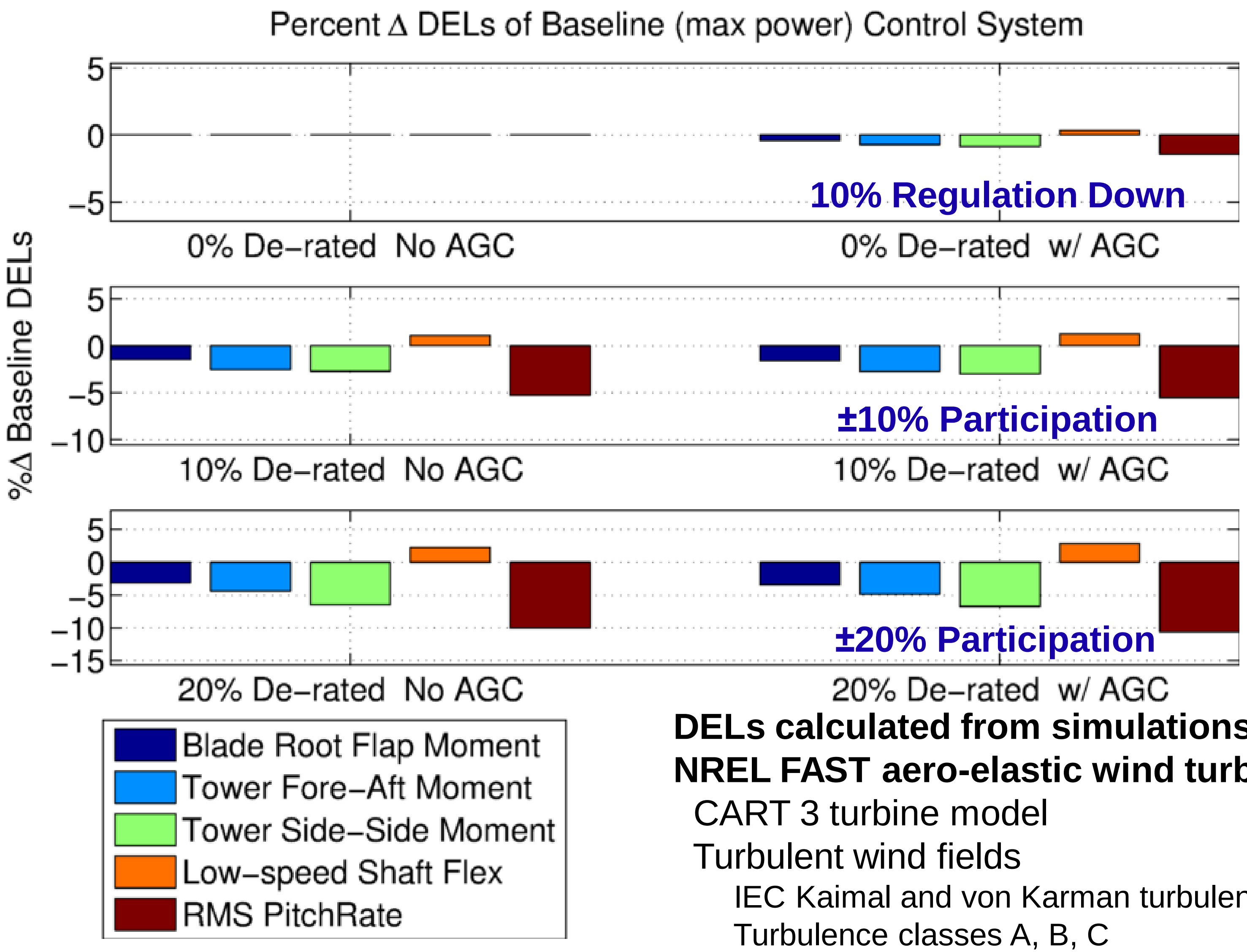


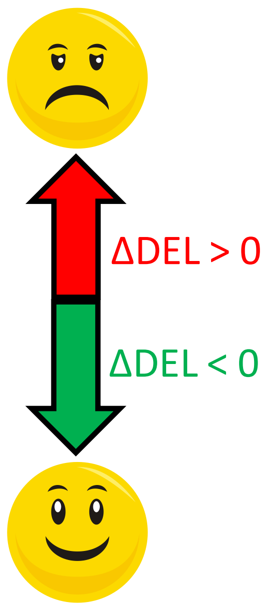
Regulation- 10% De-rating



Tradeoffs of Damage Equivalent Loads Vs. AGC Performance?

Damage Equivalent Loads (DELs)

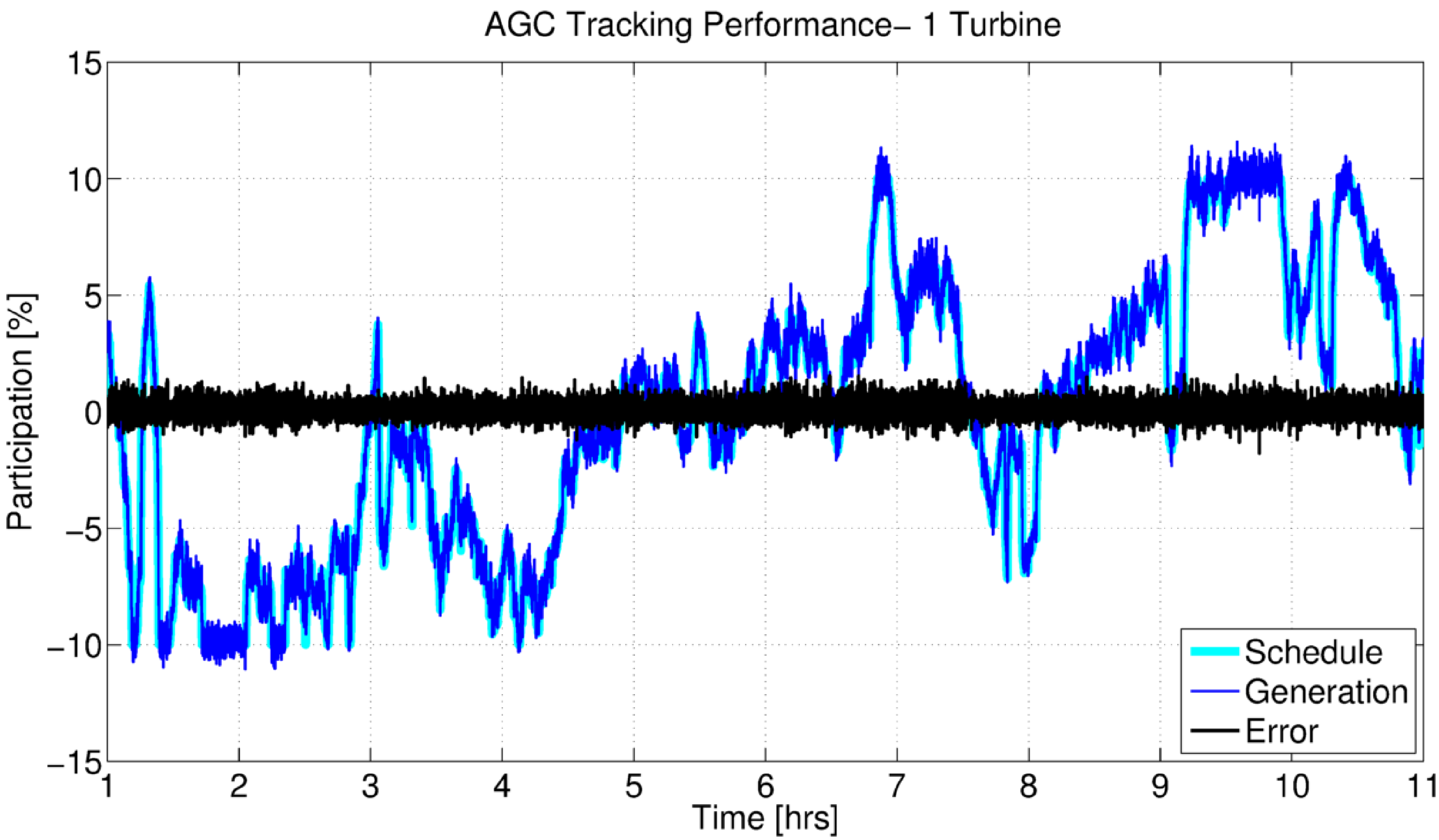




DELs calculated from simulations with NREL FAST aero-elastic wind turbine code:

- CART 3 turbine model
- Turbulent wind fields
  - IEC Kaimal and von Karman turbulence models
  - Turbulence classes A, B, C

AGC Performance- 18 m/s



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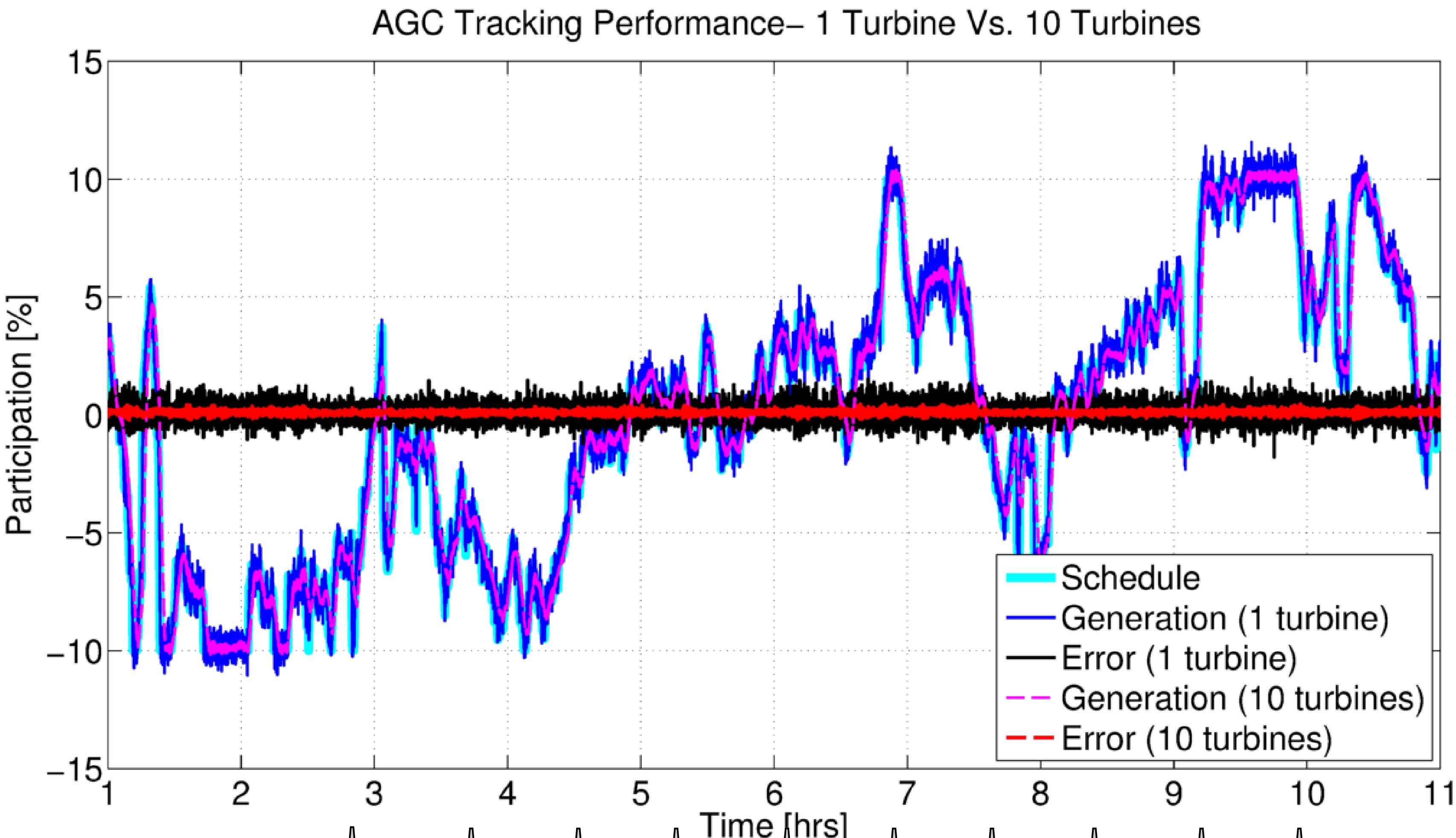
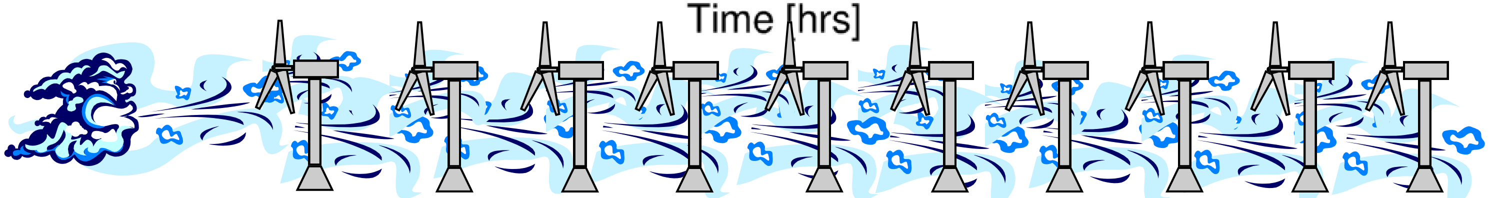
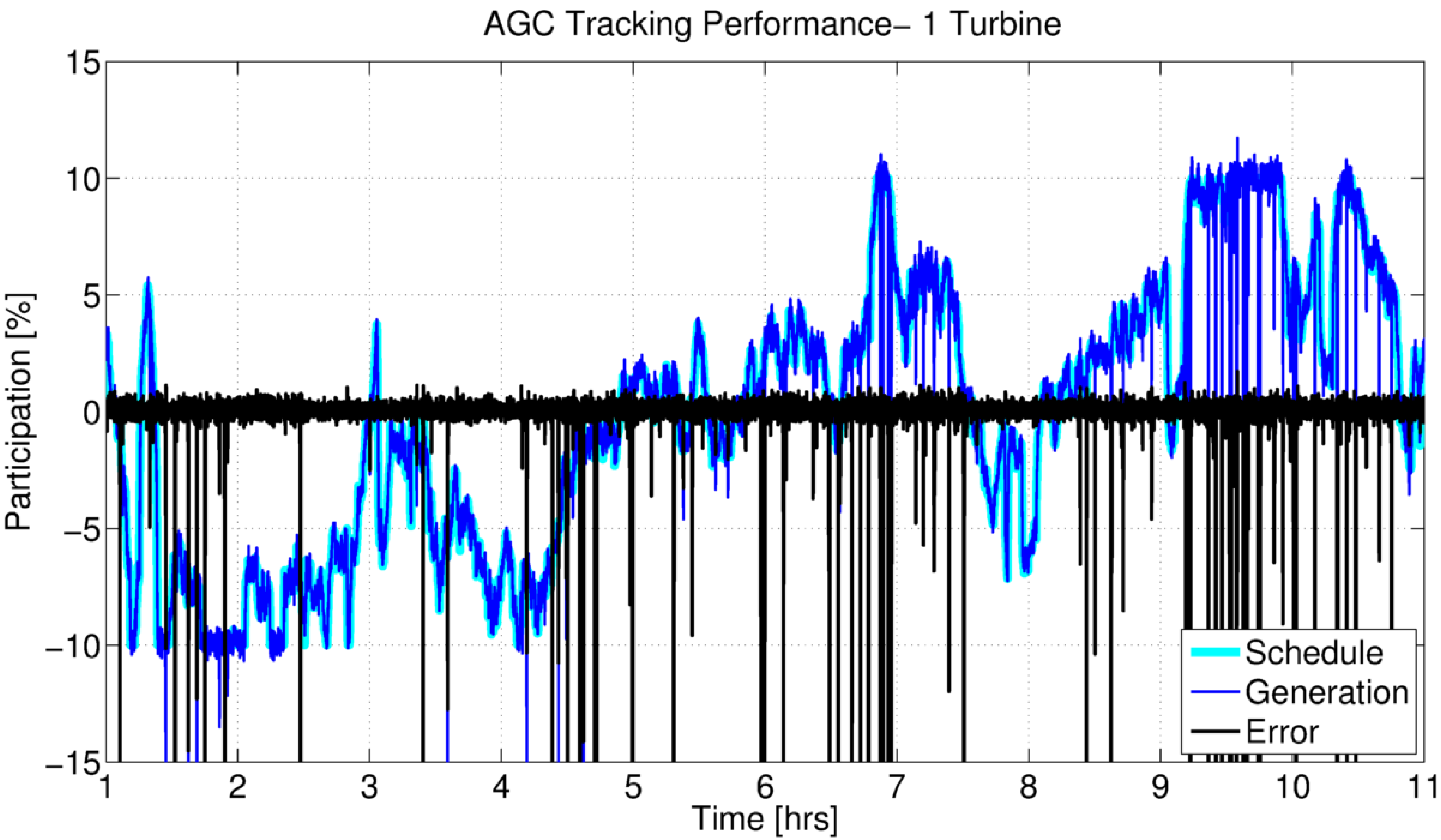




AGC Performance- 14 m/s



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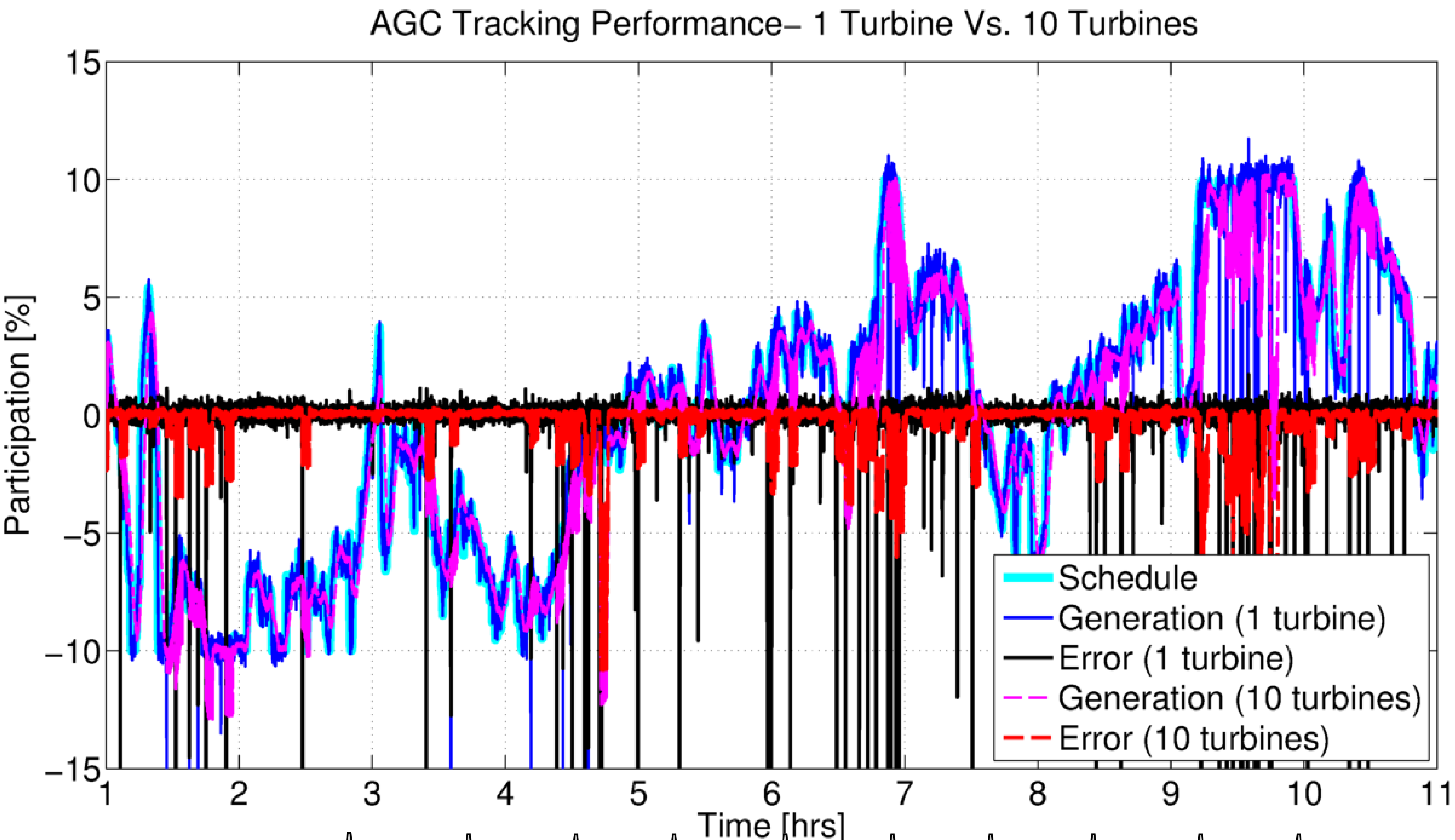
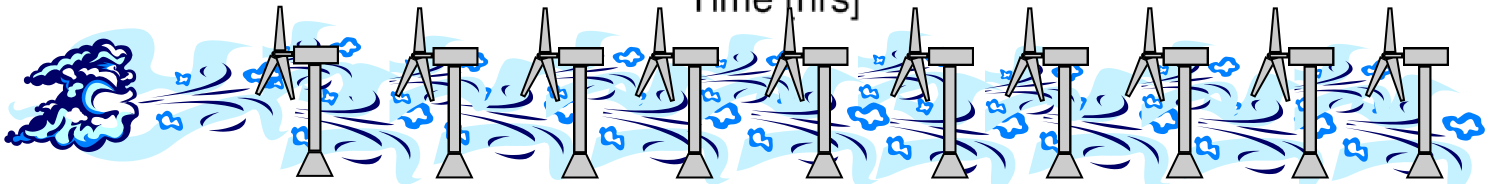




Conclusions

- De-rating has beneficial impact on DELs
  - Regulation has little impact on DELs
    - Regardless of AGC smoothing
- Wind power AGC is fast and accurate
  - Best performance in high wind speeds
    - Excess power available
- AGC error is reduced over multiple turbines
- An accurate forecasting is required
  - Probabilistic forecast over 15 min
    - Certainty that wind will not drop below rated

Future Work

Research

- Evaluate control system on:
  - Utility/offshore scale turbine
  - Wind power plant(s)
- Include forecast model
- Evaluate economics
  - Reflect DELs into a monetary cost
  - Performance based compensation
  - Penalties for underperformance
  - Optimize economic model

Implementation

- Market Adoption
  - Validation as a “qualified regulation provider”
  - Prove turbine capability
  - Probabilistic forecasts
- Improve coordination between wind power plants and grid operators
- Intelligent de-rating
  - Provide regulation at lower wind speeds

Thank You. Questions?

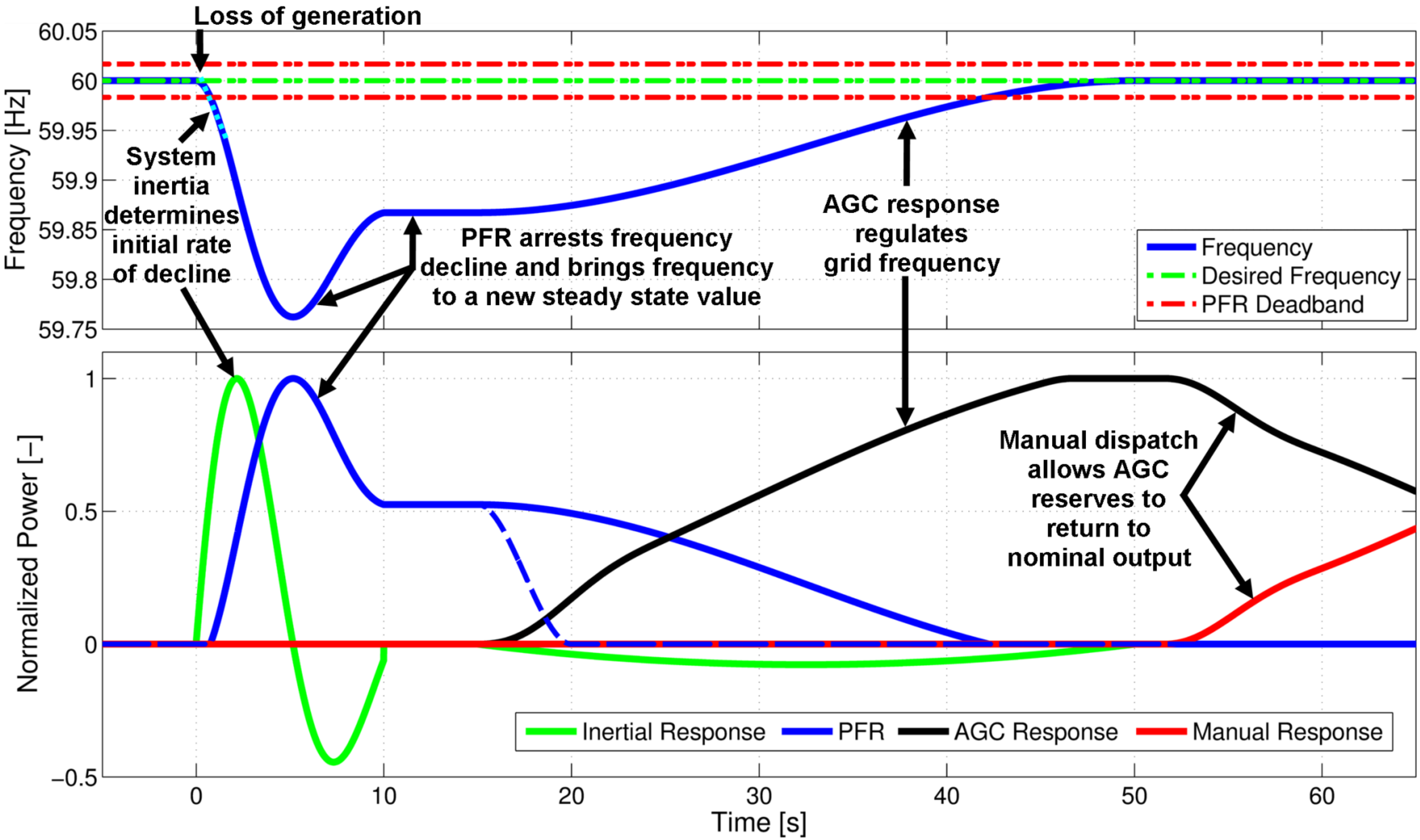
Acknowledgements and Thanks

Erik Ela,
Vahan Gevorgian,
Andrew Scholbrock
National Renewable Energy Laboratory

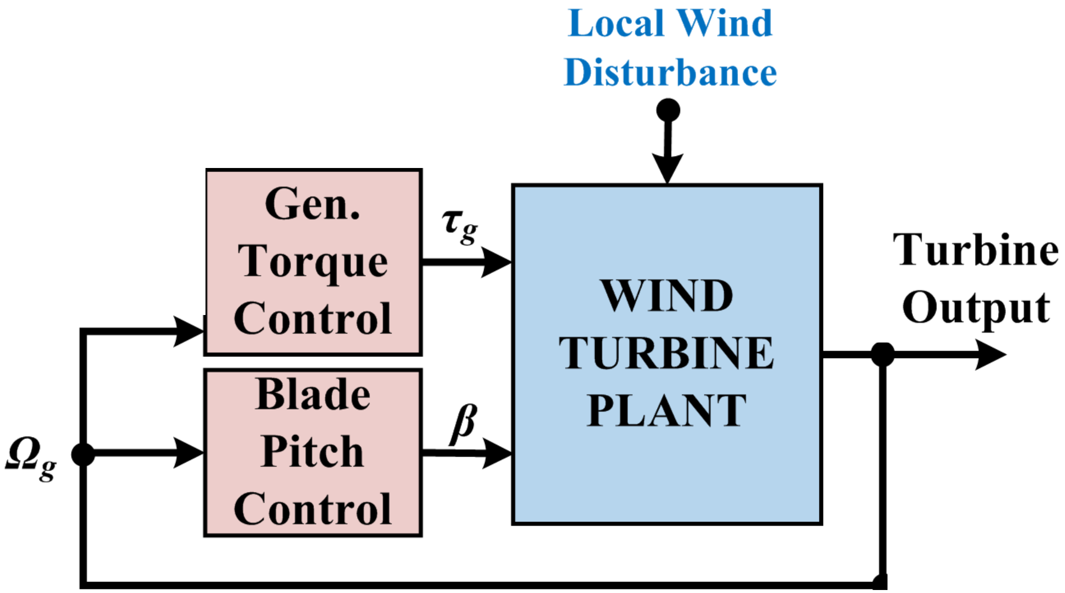
This work is produced as part of the NREL Active Power Control from Wind Power Project. This work was supported in part by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy Wind and Hydropower Technologies Program.

Supplementary Slides

Response to Frequency Event



Control System Overview



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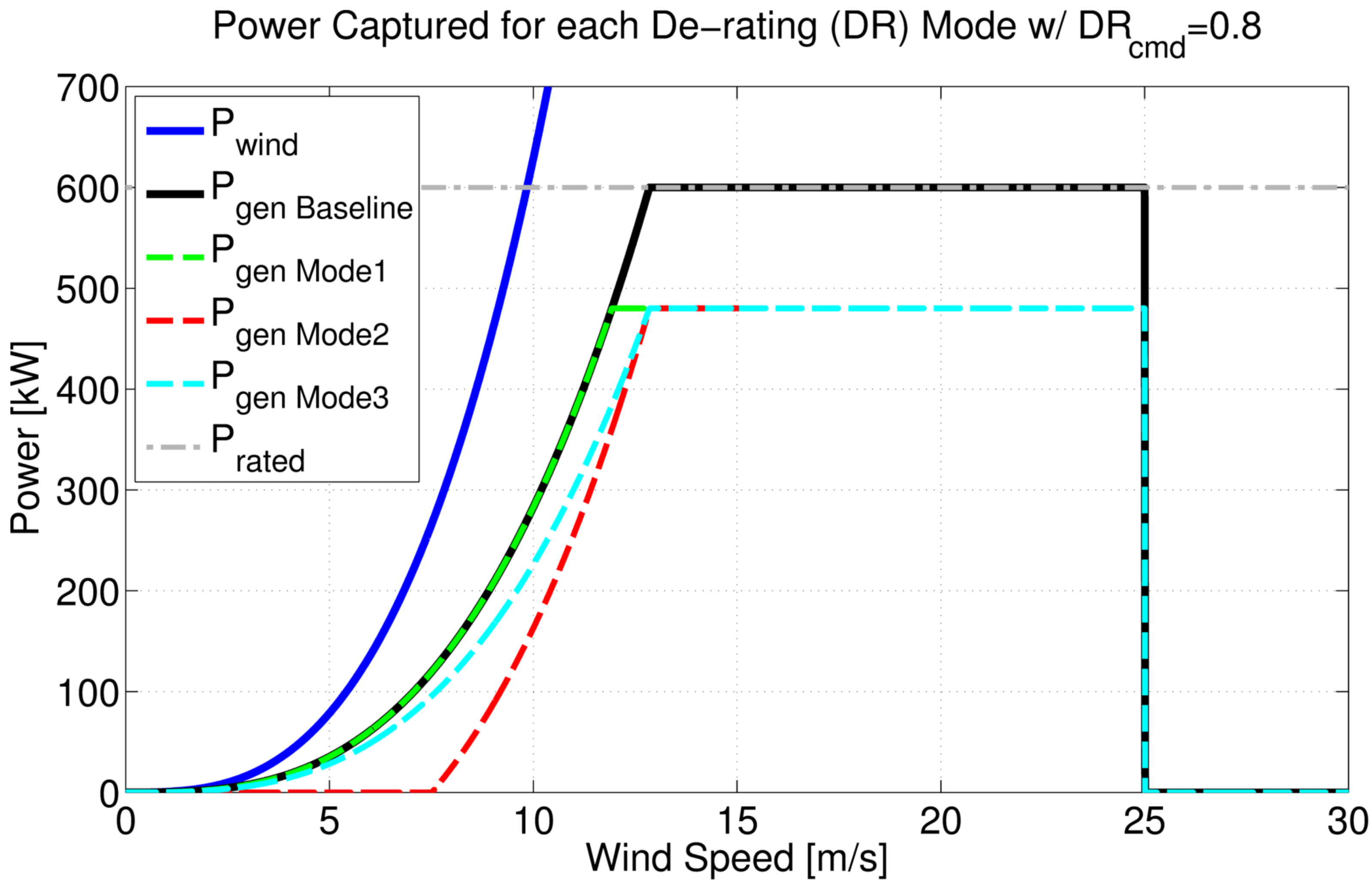
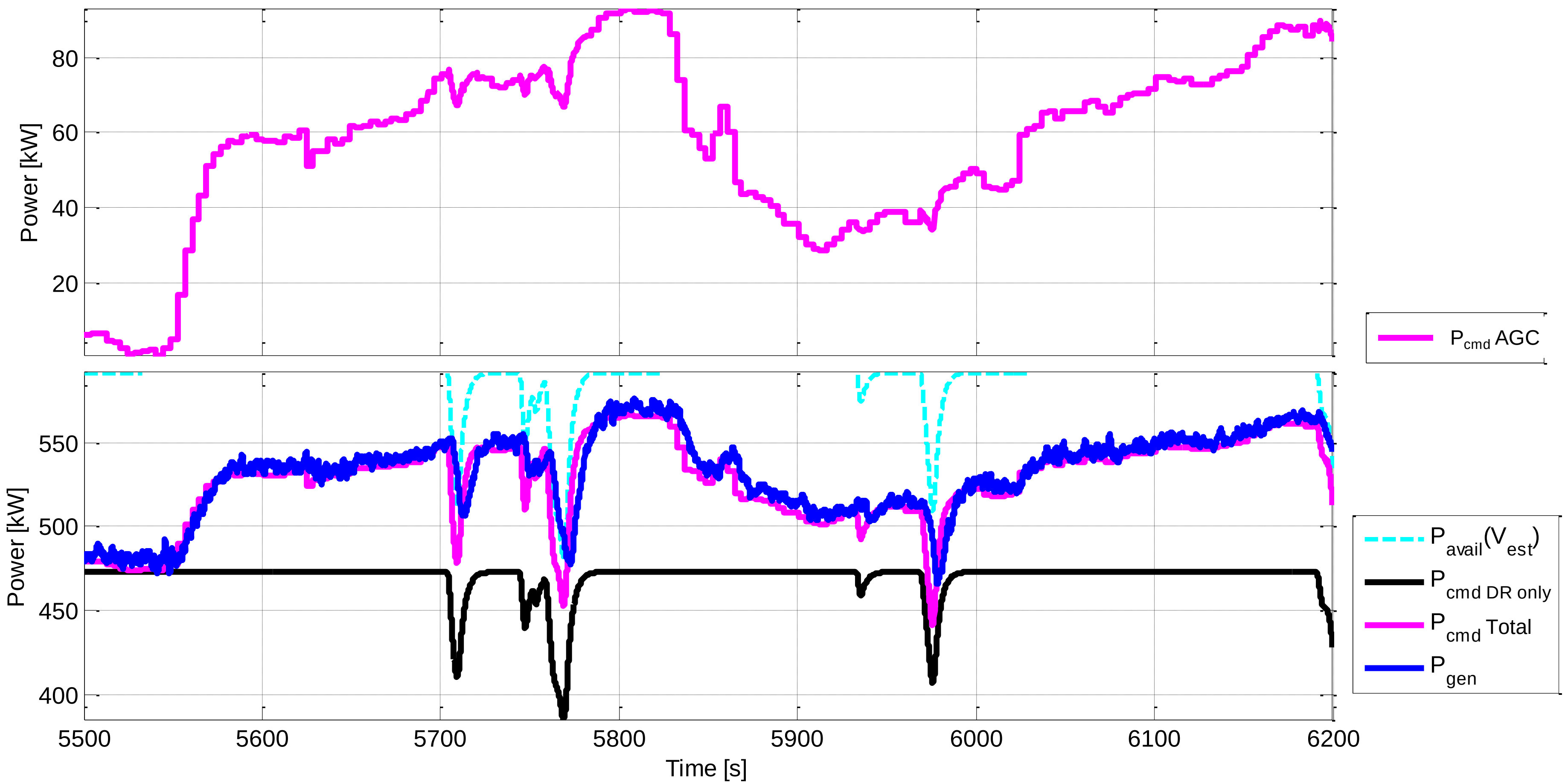
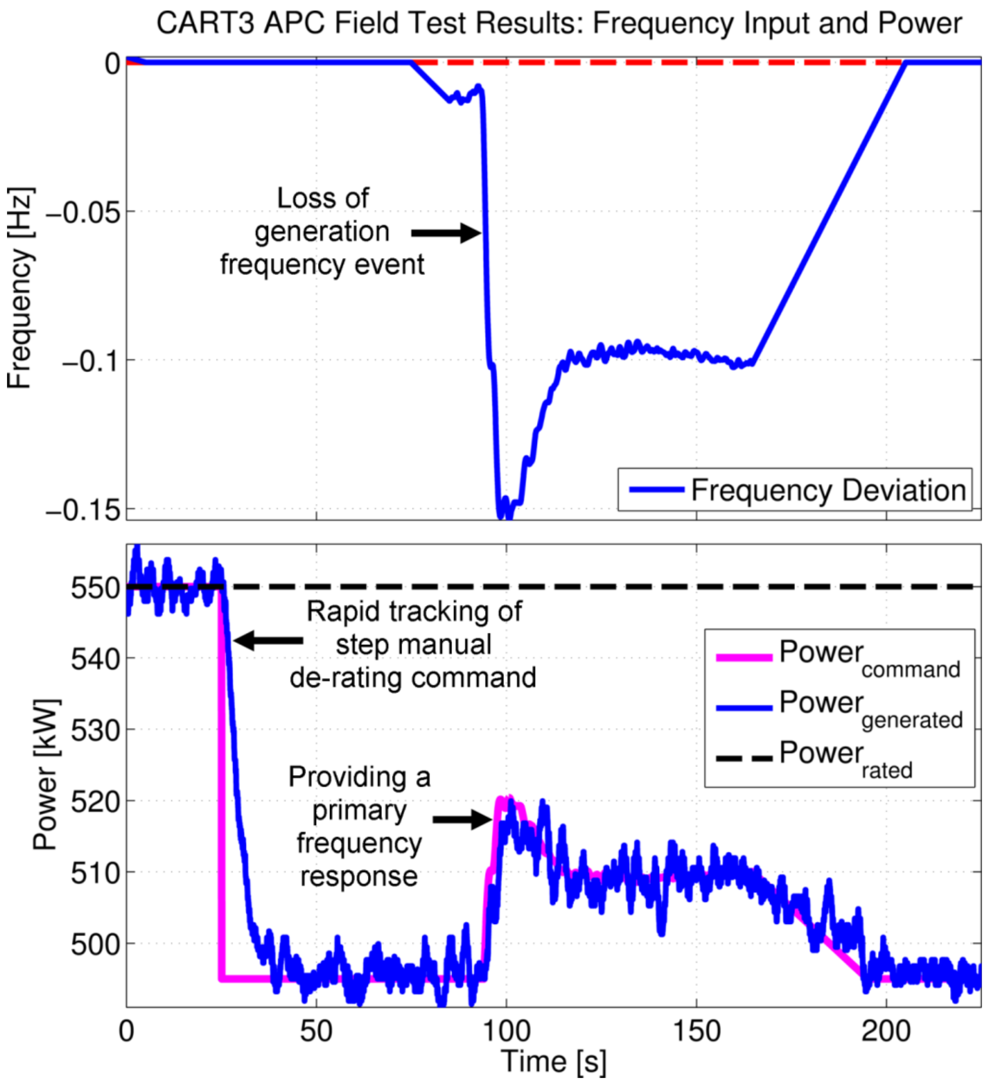
Controller De-rating Modes



CART3 Field Test



CART3 Field Test Example

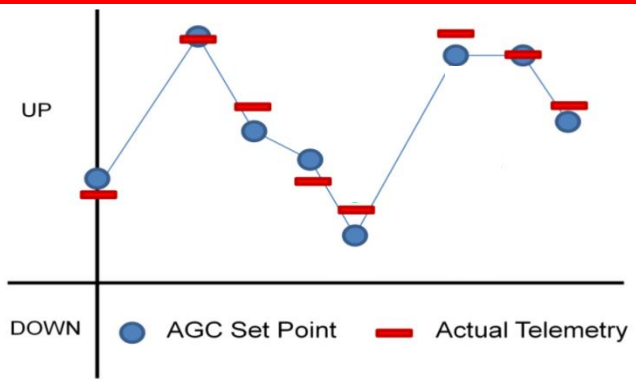


AGC Compensation

Performance based compensation model †

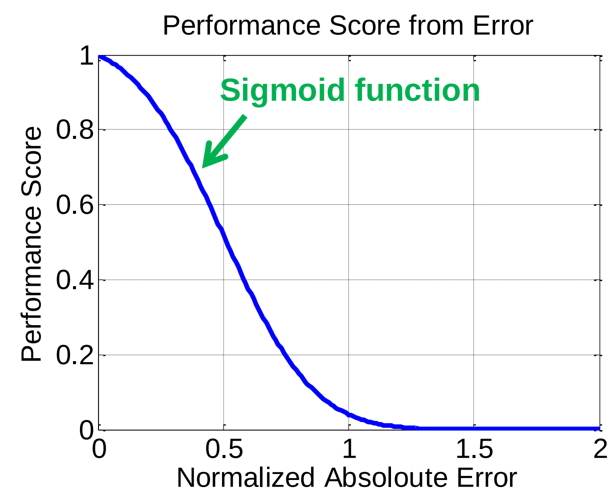
$$\begin{pmatrix}\text{Mileage}\\ \text{Payments}\\ \$\end{pmatrix} = \begin{pmatrix}\text{Actual}\\ \text{Mileage}\\ \text{MW-miles}\end{pmatrix} * \begin{pmatrix}\text{Mileage}\\ \text{Price}\\ \frac{\$}{\text{MW-miles}}\end{pmatrix} * \begin{pmatrix}\text{Performance}\\ \text{Score}\end{pmatrix}$$

We have found that a wind turbine with our APC control system can respond quicker (less delay) and more rapidly (faster ramping) than conventional power plants



CAISO, Docket No. ER12-1630-000, Apr. 27, 2012. [Online]. Available: http://www.caiso.com/Documents/April272012Compliancefilin-gregardingFERCOrder755indocketnoER12-1630-000.pdf.

- Calculated from accuracy of following AGC commands (absolute deviation)
- Weighted by Sigmoid function to benefit fast responders



† Papalexopoulos, A.D.; Andrianesis, P.E., "Performance-based pricing of frequency regulation in electricity markets," *Power Systems, IEEE Transactions on* , vol.PP, no.99, pp.1,1, 0